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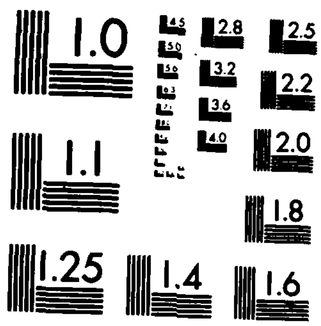

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Neutral Sheet Current Interruption and Field-Aligned Current Generation by Three Dimensional Driven Reconnection

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Abstract. We have simulated externally drived reconnection by solving the magnetohydrodynamic equations in a three-dimensional, tail-like geometry. As reconnection proceeds, the tail current is interrupted locally and field aligned currents are generated. The field aligned current flows towards the ionosphere on the morning side and away from the ionosphere in the evening. The field aligned currents flow in a narrow band at the outer edge of the plasma sheet. Thus, the simulation demonstrates that the nightside substorm current system is a natural consequence of the driven reconnection model.

Introduction

Field aligned currents in the magnetosphere have been the subject of intense study during the past decade. This is because they are believed to provide us with key information on mechanisms coupling the solar wind, the magnetosphere and the ionosphere. Two sets of large scale persistent field aligned currents have been observed within the auroral oval (Zmuda and Armstrong, 1974; Iijima and Potemra, 1976). The ionospheric Pederson currents which close these field aligned currents consume sufficient energy ($\sim 10^{11}$ watts) that the field aligned currents would disappear within a few minutes without a continuous energy supply from the solar wind.

The high latitude pair of field aligned currents, region 1 currents, are thought to be related to polar cap convection (Sato and Iijima, 1979). The lower latitude region 2 currents are more variable than the region 1 currents and are believed to be a diversion of the ring current into the ionosphere (Wolf, 1975; Sato and Iijima, 1979) associated with the divergence of the gradient and curvature drift current.

In addition to these persistent field aligned currents, several observational studies have inferred a localized transient field aligned current system near midnight during substorms (Akasofu and Meng, 1969; McPherron et al., 1973; Bostrom, 1974). This current flows into the ionosphere on the morning side and away on the evening side and is believed to connect to the ionospheric westward electrojet (see the recent reviews by Kamide (1982) and Baumjohan (1982) for a complete list of references). Atkinson (1966) suggested that such a current system would result from localized reconnection in the magnetotail and Sato (1982) has developed a model for the resulting field aligned currents based on his 2D simulation of forced reconnection. Sato's model has been sketched in Figure 1. He found that as reconnection develops, the cross tail current tends to concentrate in two thin, slow shock layers (Sato, 1979), and argued that field aligned currents will form at the shocks. However, to verify this argument, the simulations must be carried out in three dimensions. It should be noted that Akasofu and Kan (Kan and Akasofu, 1978; Akasofu, 1980) on the other hand, have argued that reconnection is not necessary to generate the substorm current systems. They have proposed a current interruption model in which the cross tail current is diverted into the ionosphere without reconnection.

Recently, Birn and Hones (1981) have presented a three-dimensional (3D) simulation of tail dynamics. Starting with Birn's (1979) self-consistent 3D tail models, they solved the magnetohydrodynamic (MHD) equations throughout the tail. In this calculation, the tearing mode instability was driven by a sudden increase in resistivity. After the resistivity was turned on, the plasma sheet began to thin and an X-type neutral line formed. Birn and Hones also observed field aligned currents in their model substorm. The field aligned currents were directed tailward on the dawnside and toward the Earth on the duskside. The polarity of these currents is opposite to that of the substorm current system described above. They suggested that their current system is responsible for the region 2 currents.

In this paper we study the generation of field aligned currents in the magnetotail by using a high resolution 3D MHD simulation of externally driven reconnection. In particular, our results confirm the field aligned current model of Sato (1982) and contrasts that of Birn and Hones (1981).

Numerical Method

In this calculation we used a rectangular coordinate version (MAGIC3R) of a 3D MHD simulation code which was originally designed to study the spheromak tilting disruption in nuclear fusion plasmas (MAGIC3C) (Sato and Hayashi, 1982). In order to maximize the spatial resolution of the model, we started with a very simple neutral sheet configuration. We adopted a Harris (1962) type magnetic field configuration. The magnetic field and plasma configurations we used are

$$\underline{B}(x,y,z) = (B_0 \tanh(z/L), 0, 0)$$
$$\rho(x,y,z) = \rho_0$$
$$T(x,y,z) = T_0 \operatorname{sech}^2(z/L)$$

where $\underline{B}$ is the magnetic field, ρ is the mass density, T is the temperature, B_0, ρ_0, T_0 are constants, and L is the half width of the neutral sheet in the z (north-south) direction.

We assumed that reconnection is triggered by a non-uniform compression of the plasma sheet somewhere in the tail accompa-

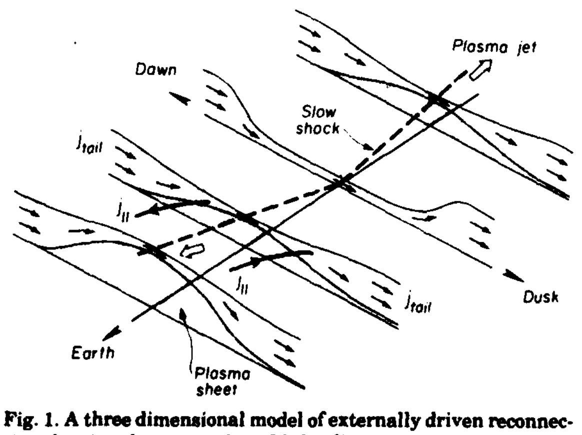

Fig. 1. A three dimensional model of externally driven reconnection showing the generation of field aligned currents (after Sato, 1982). The dashed line shows the position of the slow shock in the noon-midnight meridian. Field aligned currents flow in the slow shock region for $y \neq 0$.

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nied by the inflation of the magnetic flux in the lobe region (see Sato (1979) for a detailed description of the driven reconnection model). To model this, we expanded the 2D driven reconnection simulations of Sato and Hayashi (Hayashi and Sato, 1978; Sato and Hayashi, 1979; Sato, 1979), to 3D. In order to compress the plasma sheet, we injected a magnetized plasma (Poynting flux, kinetic energy flux and thermal energy flux) through the north and south boundary planes ($z = \pm L_z$) of the simulation box. Initially, the incoming mass flow pattern was such that

$$\rho v_z\,(z = \pm L_z) = \mp \frac{A_o}{4}\left(1 + \cos\frac{\pi x}{L_x}\right)\left(1 + \cos\frac{\pi y}{L_y}\right) \qquad (1)$$

where v_z is the z-component of the velocity, L_x, L_y, L_z are the dimensions of the simulation box, and A_o is a constant. ρv_x and ρv_y were initially set to zero. Later they were adjusted so that the mass flow vector was always perpendicular to $\underline{B}$ at the boundary. The other boundaries ($x = \pm L_x$, $y = \pm L_y$) were assumed to be free boundaries through which plasmas can freely enter or exit. The inflow pattern in (1) enabled us to reduce the physical domain of the simulation box. We did this by assuming symmetry (or anti-symmetry when appropriate) about the equator (z=0), the noon-midnight meridian (y=0), and the neutral line (x=0). Thus we were able to reduce the simulation domain by a factor of eight and thereby to increase the resolution of the model.

Recent particle simulations have demonstrated that anomalous resistivity can be generated by the lower hybrid drift instability (Winske and Liewer, 1978; Tanaka and Sato, 1981a) and that it is more strongly generated and lasts much longer in the presence of an external force that compresses the plasma sheet (Tanaka and Sato, 1981b). The resistivity is roughly proportional to the square of the diamagnetic drift velocity (Huba et al., 1978). Thus we have adopted the resistivity (η) model (Sato, 1979)

$$\eta = \alpha(V_D - V_c)^2 \text{ for } V_D > V_c$$

where V_D is the diamagnetic drift velocity and α and V_c are constants. $V_D = J/ne$ where J is the neutral sheet current, n is the plasma density and e is the electron charge.

The simulation system was a rectangular box with dimensions $L_x = 3L$, $L_y = 5L$ and $L_z = 2L$. This was implemented on a $41 \times 40 \times 51$ point grid.

In the actual calculations, all variables were normalized to the following parameters: L, length; $V_A = B_o/(\mu_o\rho_o)^{1/2}$, velocity; B_o, magnetic field; ρ_o, mass density; $B_o/\mu_o L$, current; $B_o^2/2\mu_o$, pressure; B_o^2/μ_o, energy; $\mu_o L V_A$, resistivity; and $B_o V_A$, electric field.

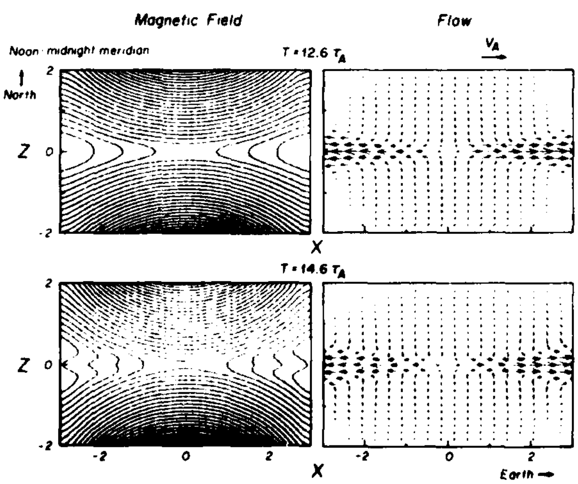

Fig. 2. Contours of constant vector potential and plasma flow vectors in the midnight meridian plane (y=0) at t = 12.6 τ_A and 14.6 τ_A.

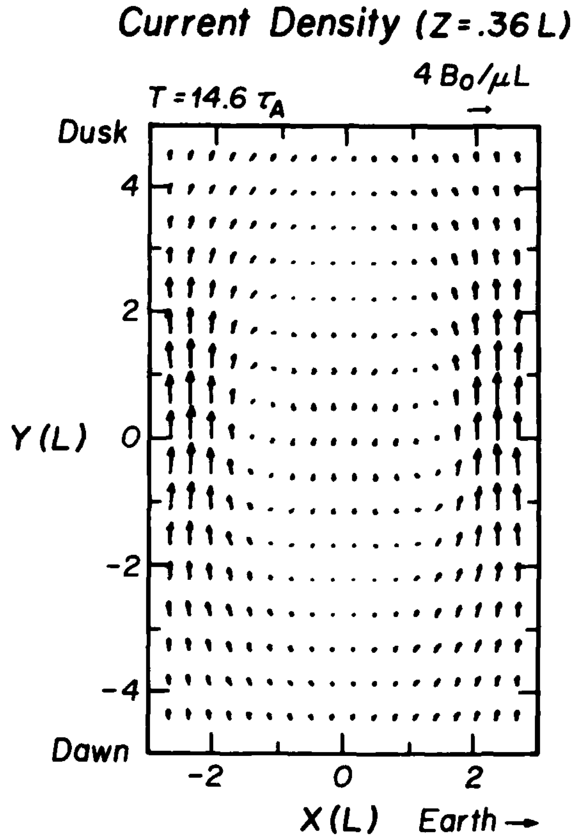

Fig. 3. Current density vectors in a plane parallel to the equator (z = .36L) at t = 14.6 τ_A.

In the computer run presented here we set $A_o = .2$, $\alpha = 0.02$ and $V_c = 3$ while B_o, T_o, ρ_o and V_D were all normalized to 1.

Tail current interruption

In Figure 2, magnetic field lines and flow vectors have been plotted in the central meridian of the tail (y=0) for two times (T = 12.6 τ_A and 14.6 τ_A). Prior to T = 14.6 τ_A, the acceleration rate (not shown) increased with time while after T = 14.6 τ_A it saturated and remained nearly constant. In the noon-midnight meridian, the results are very similar to those from the 2D simulation. In particular, a slow shock structure appears and the plasma is accelerated to approximately the local magnetosonic speed.

The direct analogy between the 2D and 3D models is invalid in planes parallel to the equator. In Figure 3, the cross tail current density has been plotted in a plane parallel to the equator and 0.36L above it. The current is almost completely interrupted in the central region. A substantial part of the current is diverted around the center. The x-component of the current earthward of the reconnection region is towards the Earth on the dawn side and away from the Earth on the dusk side. Since the field is primarily in the x-direction, this indicates the presence of field aligned currents. This can be seen more clearly in Figure 4 where magnetic field lines have been superimposed upon current density vectors in a meridian plane on the dusk side 1.15L from y=0. There are two sets of current vectors of interest. First near the outer edge of the reconnected field lines current density vectors with large field aligned components are observed. The field aligned current density ($J_\parallel = \underline{J} \cdot \underline{B}/B$) is 20% to nearly 100% of the cross tail current, and as we saw in Figure 3, the field aligned currents near dusk flow away from the Earth. These field aligned

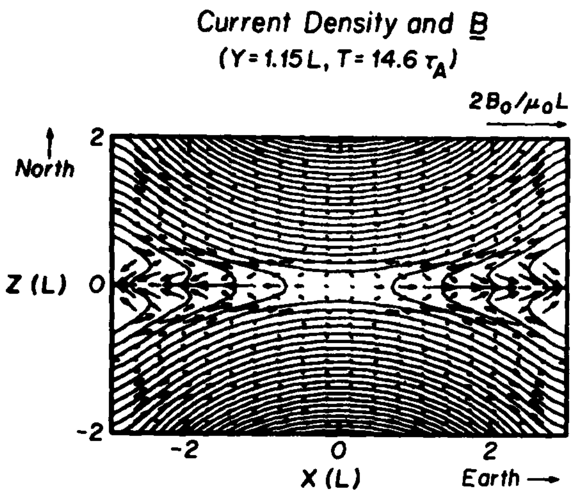

Fig. 4. Current density vectors in a plane parallel to the noon-midnight meridian on the dusk side of the tail ($y = 1.15L$) at $t = 14.6\ \tau_A$. Magnetic field lines have been superimposed on the current density vectors.

currents are observed at all y values except y=0. The amplitude ($J_\parallel$) is largest at $y = 1.67L$.

The second set of interesting current vectors (Figure 4) is just equatorward of the field aligned currents. Here, the current flows earthward and toward the equator. However, this large earthward current density does not indicate an earthward field aligned current since the field has changed direction in this region. In contrast to the field farther from z=0, the field in this region is mainly north-south. Most of this current is normal to the field. This means that the cross tail current which was initially in the y-direction now has an earthward component. In Figure 5 the current density vectors have been plotted in the equatorial plane (z=0). The earthward flow can be seen in current vortices which have formed between the reconnection region and the region of reconnected field lines. In the region of reconnected field lines the current is now from dusk to dawn rather than dawn to dusk. The $\underline{J} \times \underline{B}$ force in this region thus opposes the flow from the reconnection region. There is a small field aligned component in the near equatorial region. However, the current direction is still outward from the Earth. The field aligned current density is largest in the region of reconnected field lines farthest from the equator.

That the field aligned currents reside on the outer edge of the model plasma sheet is emphasized in Figure 6 where pressure contours have been superimposed on the current density vectors. To the accuracy of the model, the field aligned currents occur in the sharp pressure gradient which characterizes the outer edge. This is the region of the slow shock.

Discussion.

Our simulation results show that the night side substorm current system is a natural consequence of driven magnetic reconnection. In our model, the tail current is locally interrupted by three dimensional externally driven reconnection and a field aligned current system is generated with current towards the ionosphere on the morning side and away from it on the evening side. This current system presumably closes in the westward electrojet. We should point out that we have not modeled the ionosphere in this calculation. The ionosphere was treated as a perfect conductor.

The current system suggested by our calculation is consistent with the current wedge model most frequently used to interpret both magnetic field and STARE radar observations obtained near midnight during substorms (see the reviews by Kamide (1982) and Baumjohan (1982) for a complete list of references). The present results contrast the field aligned current system found in the simulation of Birn and Hones (1981). In their model, the currents are opposite to ours (i.e., away from the ionosphere in the morning and into the ionosphere in the evening). However, our results do not necessarily contradict those of Birn and Hones since the models use different boundary conditions, different initial plasma and field configurations and different resistivity models. Indeed it is possible that mechanisms analogous to both the resistive tearing model modeled by Birn and Hones and our driven reconnection mode are operating in the tail.

Since the field aligned currents reside at the edge of the reconnected field lines in our model, in the tail we would expect the substorm associated field aligned current to reside in a narrow band on the outer edge of the expanding plasma sheet. Recent observations from the ISEE spacecraft by Kelly et al. (1981) are consistent with this picture. By using $\underline{B}$ observations from both the ISEE 1 and 2 spacecraft, they inferred both the current direction and the magnitude of the current density. During plasma sheet expansions they observed intense field aligned currents limited to a small region (500-2500 km in the north-south direction) near the edge of the plasma sheet. The current direction, also, is consistent with our model.

The field aligned currents in the magnetosphere can be calculated by solving

$$\nabla \cdot \underline{J}_\parallel = B\frac{\partial}{\partial s}\left(\frac{J_\parallel}{B}\right) = c\rho\frac{d}{dt}\left(\frac{\Omega}{B}\right) + \frac{2}{B}\underline{J}_\perp \cdot \nabla B - \underline{J}_{in} \cdot \frac{\nabla N}{N} \quad (2)$$

with $\Omega = (\underline{B} \cdot \nabla \times \underline{v})/B$

$$\underline{J}_\perp = \underline{J}_D + \underline{J}_{in}$$

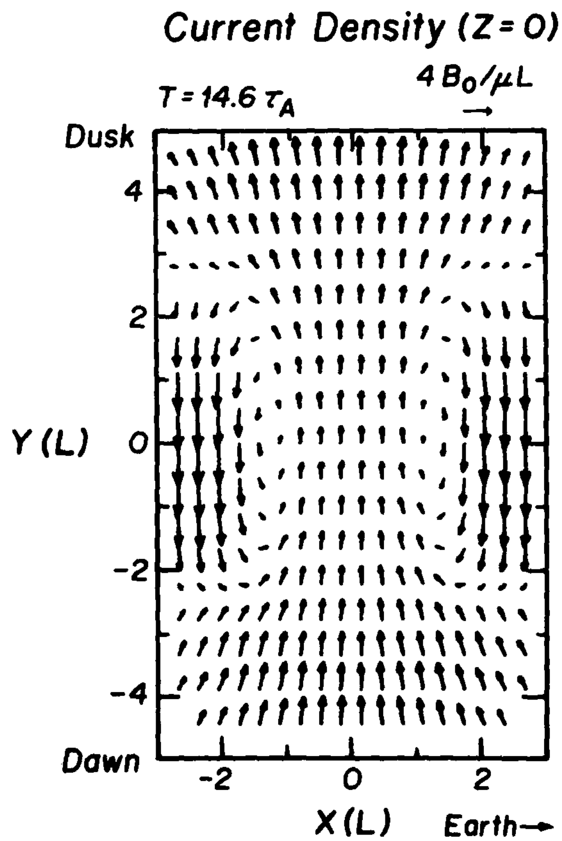

Fig. 5. Current density vectors in the equatorial plane (z=0) at t = 14.6 τ_A.

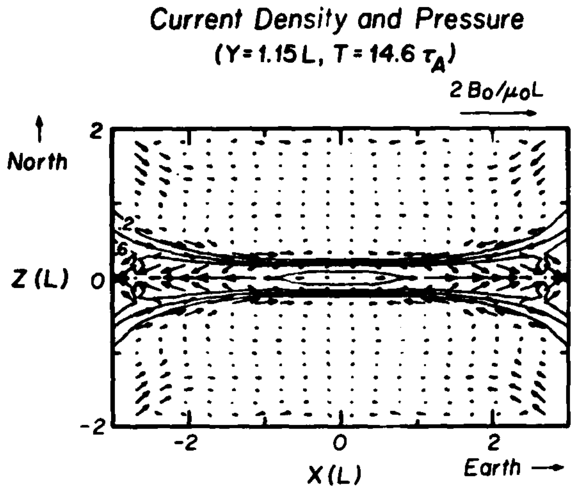

Fig. 6. The same as Figure 4 but with contours of constant plasma pressure superimposed on the current density vectors.

and $\underline{J}_D = c\underline{B} \times \nabla P/B^2$

$$\underline{J}_{in} = c\underline{B} \times \left(\frac{\rho}{B^2}\frac{dv}{dt}\right)$$

where $\underline{J}_{\parallel}$ and $\underline{J}_{\perp}$ are the parallel and perpendicular current densities, B is the magnetic field, ρ is the mass density, Ω is the vorticity, $\underline{J}_{in}$ is the inertia current, N is the density, P is the pressure and v is the velocity (Hasegawa and Sato, 1979; Sato and Iijima, 1979). The first term in (2) represents a discharge current due to convective motion and may be important for region 1 currents (Sato, 1982). The second term represents a diversion of magnetospheric current due to a magnetic inhomogeneity. This term has been used to explain the region 2 field aligned currents by diversion of the ring current (Sato and Iijima, 1979). The third current source originates where there is a density gradient in the direction of the inertia current and is usually negligibly small (Sato, 1982).

Sato (1982) has argued that the second term in (2) is responsible for the substorm field aligned current system (Figure 1). In the driven reconnection simulations, the cross tail current concentrates in two slow shock layers (see Figure 11 of Sato, 1979). In the plasma sheet this means $J_{\perp}$ should be largest at the outer edge. As reconnection develops the field intensity at the slow shocks increases due to the pile up of field lines which are driven towards the neutral sheet. In our 3D reconnection simulation this pile up is greatest at, y=0, the center of the reconnection region. In the slow shocks, $\frac{\partial B}{\partial y}\hat{e}_y$ points toward the center in both the dawn and dusk sectors. Thus $J_{\perp} \cdot \nabla B > 0$ in the dawn sector and $J_{\perp} \cdot \nabla B < 0$ in the dusk sector From (2), the field aligned current is outward from the ionosphere on the dusk side and inward towards the Earth near dawn. Thus in our simulation both the direction of the current and the concentration of the largest currents in the slow shock region (Figure 6) are consistent with the predictions of Sato's model.

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